Nuclear Instruments and Methods in Physics Research A 624 (2010) 425–427

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

# Radiation hardness studies on CMOS monolithic pixel sensors

Marco Battaglia [a,b], Dario Bisello [c], Devis Contarato [b,*], Peter Denes [b], Dionisio Doering [b], Piero Giubilato [b,c], Tae Sung Kim [b], Serena Mattiazzo [c], Velimir Radmilovic [b], Sarah Zalusky [a,b]

[a] Department of Physics, University of California at Berkeley, CA 94720, USA
[b] Lawrence Berkeley National Laboratory, 1 Cyclotron Road, Berkeley, CA 94720, USA
[c] Dipartimento di Fisica, Università di Padova and INFN, Sezione di Padova, I-35131 Padova, Italy

ARTICLE INFO

Available online 2 April 2010

*Keywords:*
Monolithic active pixel sensors
Silicon pixel detectors
Radiation tolerance

ABSTRACT

This paper presents irradiation studies performed on a CMOS monolithic pixel sensor prototype implementing different optimizations of the pixel cell aimed at a superior radiation tolerance. Irradiations with 200 keV electrons up to a total dose of 1.1 Mrad have been performed in view of the utilization of such a design in Transmission Electron Microscopy (TEM) applications. Comparative irradiations were performed with 29 MeV protons up to a 2 Mrad total dose and with 1–14 MeV neutrons up to fluences in excess of $10^{13}\,n_{eq}\,cm^{-2}$. Experimental results show an improved performance of pixels designed with Enclosed Layout Transistor (ELT) rules and an optimized layout of the charge collecting diodes.



## 1. Introduction

CMOS monolithic pixel sensors have been shown in the past decade to be an attractive option for applications ranging from high resolution particle tracking [1] to fast imaging in Transmission Electron Microscopy (TEM) [2,3] and beam monitoring. In order to withstand the large radiation fluxes received by the sensors in these applications, an optimized design is needed with respect to standard devices.

In High-Energy Physics (HEP), CMOS monolithic pixels are a favored option for future vertex trackers at $e^+ e^-$ colliders due to their higher spatial resolution and much reduced material budget compared to hybrid pixel sensors. The ionising dose at the position of the innermost vertex detector layer is expected to be $\sim 50\,\mathrm{krad\,yr^{-1}}$ at a high energy linear collider and $\sim 0.5-1\,\mathrm{Mrad\,yr^{-1}}$ at a high luminosity B-factory, while the anticipated yearly non-ionising fluences are in the range $10^{11}$–$10^{12}$ $n_{eq}$ $cm^{-2}\,yr^{-1}$. In TEM applications, CMOS pixels achieve single electron sensitivity through direct detection, while the thin collection layer, limited to the typically $10-15\,\mu$m thick epitaxial layer, ensures an excellent point spread function. Moreover, a high readout speed can be achieved, thus favoring fast dynamic imaging. Considering the typical yearly usage of such a detector in TEM, a tolerance to ionizing doses in excess of 1 Mrad is desirable. Furthermore, radiation hardness to doses up to several Mrad may be required for beam imaging applications, such as real-time monitoring of beam position and profile in hadrontherapy.

A CMOS monolithic pixel prototype, the LDRD2-RH chip described in Section 2, has been designed exploring several layout optimizations of the pixel cell aimed at a tolerance to a few Mrad ionising dose and to non-ionising fluences of order $10^{13}\,n_{eq}$ $cm^{-2}$. Its design is discussed in detail in Ref. [4]. The sensor was originally intended as the prototype for a large scale CMOS imager to be deployed in TEM applications. The response of the LDRD2-RH chip to electrons in the energy range of interest for TEM (80–300 keV) has been extensively characterized in terms of energy deposition, charge spread and point spread function in Refs. [4,5]. This paper will report on comparative irradiation studies performed with electrons, protons and neutrons in order to evaluate the performance of the different layout options (Section 3).

## 2. Sensor design and experimental setup

The LDRD2-RH chip (Fig. 1) was manufactured in AMS 0.35 μm CMOS-OPTO technology with an epitaxial layer of 14 μm nominal thickness, and features an array of $96 \times 96$ pixels on a 20 μm pitch. The sensor, designed as a variation of a previous non-radiation-hard design [6], is subdivided in several sectors with different layout optimizations of the charge collecting diode. Pixels implement a simple 3-transistor (3T) analog architecture, designed both with and without Enclosed Layout Transistor (ELT) rules for comparison. The chip is read out in a rolling-shutter mode, ensuring a constant integration time across the pixel

* Corresponding author.
*E-mail address:* DContarato@lbl.gov (D. Contarato).

0168-9002/$ - see front matter © 2010 Elsevier B.V. All rights reserved.
doi:10.1016/j.nima.2010.03.156

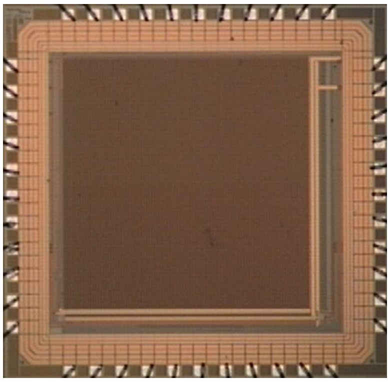

**Fig. 1.** Picture of the LDRD2-RH chip.

matrix. Pixels are clocked up to a maximum frequency of 25 MHz, corresponding to an integration time of 184 μs, and are read out through a custom FPGA-driven acquisition board equipped with a set of 14 bit, 40 MSample $s^{-1}$ ADCs. The DAQ is connected to a National Instrument digital acquisition board installed on a control PC, and data are acquired and monitored by a LabView-based custom software.

## 3. Irradiation studies

The radiation hardness of the LDRD2-RH chip has been assessed by comparing the sensor response before and after irradiation with 200 keV electrons, 29 MeV protons and $\simeq 1-14$ MeV neutrons. Pixel noise, leakage current and charge collection properties have been studied for the different irradiations. All tests have been performed at room temperature.

In CMOS sensors, ionising radiation leads to trapping of positive charge in the field oxide, resulting in inversion of the silicon at the interface and thus in an increased leakage current in the charge collecting diode. Non-ionising energy loss (NIEL) can displace silicon bulk atoms and create defects in the detector sensitive volume; this is true especially in the vicinity of the diode where the silicon is depleted, and can lead to a bulk current that adds up to the diode leakage current. The threshold energy for electrons to cause displacement damage in silicon is 260 keV [7], and 200 keV electrons are thus expected to create only ionising damage and to not affect the silicon bulk. On the other hand, 29 MeV protons damage the sensor via both ionisation and NIEL, while neutrons are expected to affect the silicon only via bulk damage.

The irradiation with 200 keV electrons has been performed at the LBNL National Center for Electron Microscopy (NCEM). The sensor has been irradiated in steps up to a total dose of 1.11 Mrad, and the pixel leakage current has been monitored after each step as reported in Ref. [4]. The irradiation with 29 MeV protons was performed at the BASE facility of the LBNL 88-in. Cyclotron [8]. A sensor was irradiated in steps up to a total integrated fluence of $8.5\times10^{12}$ p $cm^{-2}$, corresponding to a total dose of 1.98 Mrad. A flux of $\sim 3\times10^{8}$ p $cm^{-2}\,s^{-1}$ was employed throughout the irradiation. Similarly to the electron irradiation, the pixel dark level was recorded at the end of each irradiation step, in order to monitor the variation of leakage current and pixel noise as a function of the delivered dose.

Fig. 2 compares the results from the 200 keV electron and the 29 MeV proton irradiation for pixels designed with ELT rules and three layout options (labelled as A–C) for the charge collecting diodes, implemented in different sectors of the chip. All three layouts implement a $p^+$ guard-ring around the charge-collecting

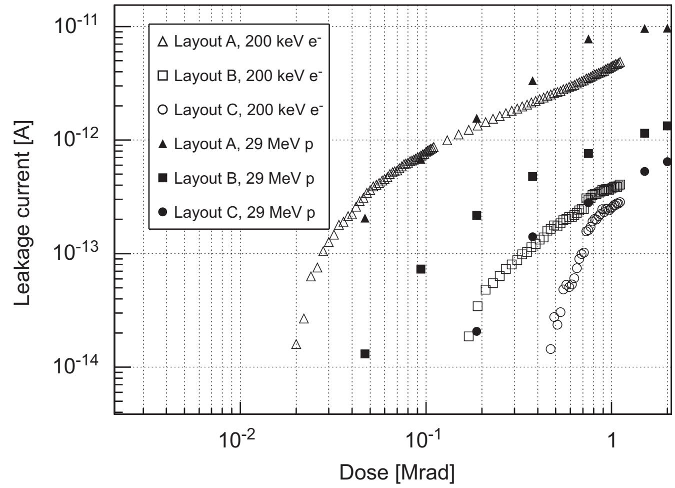


**Fig. 2.** Pixel leakage current as a function of the 200 keV electron and 29 MeV proton dose for pixels with ELT transistor design and different layouts of the charge collecting diode. The data referring to electron irradiation is taken from [4].

diode. Layout A has thick field oxide between the diode implant and the guard-ring. Layouts B and C have thin oxide between the diode implant and the guard-ring, with layout B having a shallower $n^+$ diode implant [4]. In both irradiations, the best performance among all ELT designs is obtained in pixels designed with layout option C, which shows only a moderate increase of the leakage current; a thinner oxide limits the build-up of positive charge trapped in the oxide and is thus beneficial in limiting the pixel leakage. At equal doses, a larger leakage current is associated with proton irradiation, hinting at a possible contribution from displacement damage.

Neutron irradiation has been performed at the LBNL 88-in. Cyclotron by exposing one LDRD2-RH sensor to neutrons produced from 20 MeV deuteron breakup on a thin Be target [9]. The detector was located 8 cm downstream from the target and activation foils were placed just behind it to monitor the delivered fluence. Deuteron breakup produces neutrons on a continuous spectrum from $\sim 1$ MeV up to $\sim 14$ MeV. A beam current of 800 nA was used, corresponding to an estimated flux at the chip position of $\simeq 4\times10^{8}$ n $cm^{-2}\,s^{-1}$. The total fluence was measured from the $\gamma$ activity of activation foils to be in excess of $1.2\times10^{13}$ n $cm^{-2}$. After irradiation, no significant change in the sensor leakage current or noise could be observed.

The detector charge-to-voltage conversion gain and its noise in equivalent noise charge (ENC) have been determined by exposing the sensor to a $^{55}$Fe source and by reconstructing the position of the 5.9 keV X-ray peak before and after irradiation. Results obtained on the pixels designed with layout C after the three irradiation experiments described above are summarised in Table 1. We here note that the pre-irradiation noise values for the electron and proton irradiations are significantly higher compared to the neutron case because of the longer interconnection cables between the detector board and the DAQ system required in the first two experiments. No significant change in pixel noise is observed, while a 35% decrease in gain is observed after both electron and proton irradiation. A similar decrease in gain of $\simeq 1.35$ was observed on the electron irradiated sensor from the test of the pixel response to charged particles (200 keV and 1.5 GeV electrons). As reported in Ref. [4], after correcting for the gain change, the noise and energy deposition distributions were in good agreement with the pre-irradiation ones, indicating that the pixel charge collection properties have not been affected, and that the change in gain might be due to

**Table 1**
Charge-to-voltage conversion gain and pixel noise measured before and after the three irradiations in pixels implementing diodes designed with layout option C and ELT transistors.

| | Before irradiation | After irradiation |
|---|---|---|
| $e^-$ irradiation | | |
| Pixel noise | $(130 \pm 6)$ $e^-$ ENC | $(122 \pm 6)$ $e^-$ ENC |
| Calibration | $(26.7 \pm 0.6)$ $e^-$/ADC | $(36.3 \pm 0.8)$ $e^-$/ADC |
| p Irradiation | | |
| Pixel noise | $(128 \pm 5)$ $e^-$ ENC | $(126 \pm 5)$ $e^-$ ENC |
| Calibration | $(25.9 \pm 0.5)$ $e^-$/ADC | $(34.9 \pm 0.9)$ $e^-$/ADC |
| n Irradiation | | |
| Pixel noise | $(69 \pm 3)$ $e^-$ ENC | $(64 \pm 5)$ $e^-$ ENC |
| Calibration | $(25.2 \pm 0.3)$ $e^-$/ADC | $(24.4 \pm 0.4)$ $e^-$/ADC |

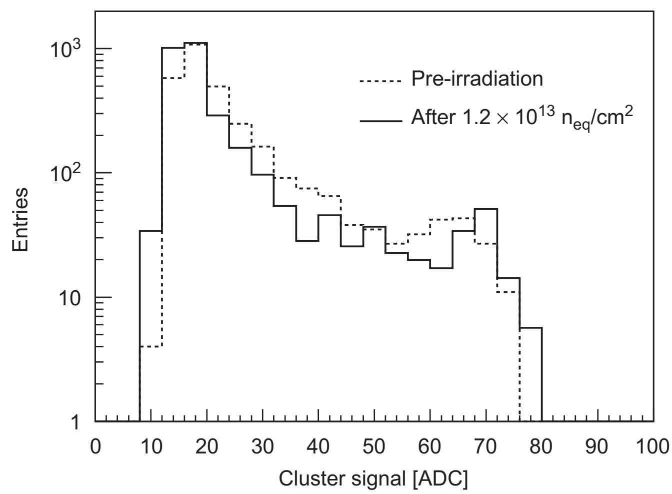


**Fig. 3.** Single pixel spectrum obtained with $^{55}$Fe on the pixels designed with layout C and ELT transistors before and after neutron irradiation. The position of the 5.9 keV peak is visible at 65–70 ADC counts.

radiation effects on the detector output electronics, which is designed with a standard layout and is thus more sensitive to (ionizing) radiation than the transistors in the ELT pixel cells.

Fig. 3 shows the $^{55}$Fe spectrum in the pixel sector equipped with layout C diodes and ELT transistors before and after neutron irradiation, while Fig. 4 shows the corresponding single pixel noise distributions. Neutron irradiation leaves the sensor gain basically unchanged, suggesting that the effect of bulk damage is still negligible at the fluences attained, and that the increase of leakage current observed after proton irradiation is mainly due to ionisation damage. However, we note here that the hardness factor of 29 MeV protons with respect to 1 MeV neutrons is 2.346 [10], yielding a maximum equivalent fluence for protons of $2 \times 10^{13}$ $n_{eq}\,cm^{-2}$, almost a factor two larger than the total fluence achieved with the neutron irradiation.

## 4. Conclusions

A CMOS monolithic pixel sensor with an optimized design of the pixel cell for improved radiation tolerance has been designed

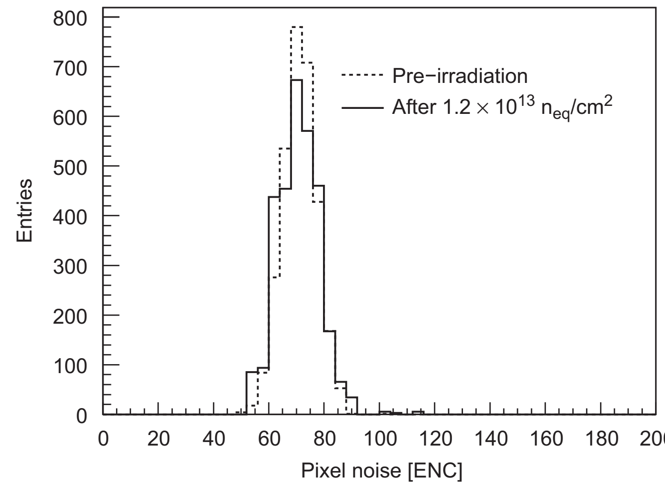


**Fig. 4.** Pixel noise distribution for the pixels designed with layout C and ELT transistors before and after neutron irradiation.

and tested. The sensor radiation tolerance has been assessed against 200 keV electrons up to a total dose in excess of 1 Mrad, 29 MeV protons up to a total dose of 2 Mrad and with 1–14 MeV neutrons up to equivalent fluences in excess of $1 \times 10^{13}$ $n_{eq}\,cm^{-2}$. After electron and proton irradiation, only a moderate increase in the pixel leakage current was measured for pixels implementing transistors designed with ELT rules and an adequate layout of the charge collecting diode. At equal ionizing doses, a larger leakage current was found associated with proton irradiation. No significant change in leakage current or noise could be observed after neutron irradiation, suggesting that the effect of bulk damage is still negligible at the fluences considered.

The best performing pixel layout has been used in the design of a large scale prototype, the TEAM1K detector, featuring $1024 \times 1024$ pixels of 10 μm pitch and multiple parallel outputs for high frame rate. The chip, also manufactured in the AMS 0.35 μm CMOS-OPTO process, is currently under test and will be deployed as the demonstrator of a high-resolution, fast and radiation-hard CMOS pixel imager for the TEAM electron microscope at the LBNL National Center for Electron Microscopy.

## Acknowledgements

This work was supported by the Director, Office of Science of the US Department of Energy under Contract no. DE-AC02-05CH11231. The authors would like to thank the staff of the LBNL National Center for Electron Microscopy and 88-in. Cyclotron for the assistance in the irradiation experiments.

## References

[1] R. Turchetta, et al., Nucl. Instr. and Meth. A 458 (2001) 677.
[2] G. Deptuch, et al., Ultramicroscopy 107 (2007) 674.
[3] P. Denes, et al., Nucl. Instr. and Meth. A 579 (2007) 891.
[4] M. Battaglia, et al., Nucl. Instr. and Meth. A 598 (2009) 642.
[5] M. Battaglia, et al., Nucl. Instr. and Meth. A 605 (2009) 350.
[6] M. Battaglia, et al., IEEE Trans. Nucl. Sci. NS-55 (2008) 3746.
[7] G. Lindström, Nucl. Instr. and Meth. A 512 (2003) 30.
[8] M.A. McMahan, Nucl. Instr. and Meth. B 241 (2005) 409.
[9] D.L. Bleuel, et al., Nucl. Instr. and Meth. B 261 (2007) 974.
[10] A. Vasilescu, G. Lindström, Displacement damage in silicon, online compilation available at 〈http://sesam.desy.de/members/gunnar/Si-dfuncs.html〉.